NPS55PK72071A

NAVAL POSTGRADUATE SCHOOL

Monterey, California

UNDERWATER DISPLAY VISIBILITY AS INFLUENCED

BY

TURBIDITY, DISPLAY BACKGROUND COLOR,

AND THE COLOR AND INTENSITY OF ILLUMINATION

By

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July 1972

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ABSTRACT

The purpose of this study was to determine the effects of water turbidity, display background color, and the color and intensity of illumination on a visual reading task in a dark, flooded environment. The reading task was to read a voltmeter and make a correct oral report of the reading.

The sixteen subjects used in this study were allowed to set the intensity at a level which they felt was the minimal needed without sacrificing accuracy or speed in the reading task. As was expected, the results show no difference in the effects of the other variables since subjects apparently adjusted the intensity to a level which equalized the effects of the other variables in any given condition. There was a significant statistical difference in the response times under the two water turbidities used but this difference was only .07 seconds.

The error rate was constant, with no variable having a greater effect on the error rate than did other variables. The expected error rate over all variables was .092 errors per each trial taken.

Prepared by:

FORWARD

This experimental investigation was sponsored by G. E. Miller, Code 3400, Naval Electronics Laboratory, San Diego, California. The work was performed by the author in the Human Engineering and Man-Machine Systems Design Laboratory of the Naval Postgraduate School, Monterey, California. To expedite the transfer of information, this report will be referred to as Report No. 2 in the underwater vision investigations for Mr. Miller.

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I. INTRODUCTION

This report is the second of two submitted to the sponsor on the subject of underwater visibility of displays under different environmental conditions. Specifically, this study describes an investigation into the effects of water turbidity, background color of the display, instrumentation lighting color and subject controlled intensity of illumination on the ability of a human operator to make a numerical reading while viewing through water. This is comparable to the problems faced by operators of the Navy's submersible diving vehicles (SDV) which this research is intended to simulate. Many other variables also affect the operator's performance as well. For scientific clarity and conciseness, the reader is referred to the following for a good overview of the research previously done in this area: Poock and Ruckner (1972), Kinney, Luria and Weitzman (1967), and Duntley (1963).

II EXPERIMENTAL PROCEDURE

The following is a description of the experimental apparatus, design, and subjects used in this research.

A. DISPLAY

The displays used for this study were circular 0-10 volt D.C. voltmeters (Weston Electrical Instrument Corp. Model 301). Two display conditions were used in the experimentation. One display was the actual voltmeter with black lettering on white background. A photographic negative reproduction provided an identical display with white lettering on a black background.

Each instrument was illuminated by a "donut" shaped circular plastic (lucite) ring, which was mounted on the front periphery of each meter and used to spread the light evenly from the following bulbs. The lucite ring contained twelve G.E. No. 44 six volt bulbs which were inserted into drilled wells from the outside of the ring and slanted inward toward the meter face. Four equally spaced bulbs were illuminated at any time to produce white, red, or green illumination on the meter. Green and red illumination were obtained by using Kodak Wratten gelatin filters in front of the respective bulbs used for those colors. The red filter was a Wratten number 29 with dominant wavelength of 632.7 nanometers. The green filter was a Wratten number 61 with dominant wavelength of 533.8 nanometers. (These wratten filters were chosen to correspond as closely as possible to the colors used in the concurrent work of Miller and Kirtz (1972).)

Two identically calibrated meters were used with the exception that one had black lettering on white background and the other vice versa. Each meter could easily be inserted or removed from the circular lucite ring and the desired illumination color on the face of the meter could easily be set to white, red or green by a simple electrical switching arrangement.

The voltmeters had a 90 degree circular scale swept by a pivoting pointer. The descriptive data of the meters are listed below:

1) Number Size Book style, with a height of .108", stroke width of .015" or a stroke width to height ratio of 1:7.

2) Indicia Size Indicia had a width .017" for the major and .010" for the minor indicia. The height was .156" for the major indicia and .087" for the minor indicia.

Brightness of the meters was determined by measuring the reflectance of the black and white surfaces being used. The white used on the meters showed a reflectance of 30 percent and black showed a reflectance of 4 percent using white illumination. The brightness contrast was 86.7 percent and the brightness ratio was approximately 7.5:1.

B. APPARATUS

In order to simulate the underwater environment a rectangular tank (2' × 2' × 6') was constructed of 3/4" exterior grade plywood. A standard oval face mask was mounted in the center of one end. The tank was calked, sealed with a commercial yacht sealer, and the inside painted black. The entire tank was then mounted on a frame of 2x4 pine with the center of the face mask 48 inches above the floor to allow subjects to be comfortably seated. The tank also had a lid to eliminate ambient illumination.

The test display which was positioned inside a water tight 1/4" plexiglass box, was mounted in such a way as to be level to the face mask when the box was placed inside the tank. Viewing distance was kept constant at 12". Color illumination was achieved by the previously mentioned "donut" ring.

A shutter was located between the face mask and the display to control the actual time of exposure to the subject. Timing, and shutter control were accomplished with a Lafayette Instrument Company Multi Reaction Timer, Model 6302 BX, coupled with a Lafayette Voice Time Control, Model 6602 A.

A second identical matching meter face, either black on white or white on black depending on which test display was being used, was located directly above the test display and also respectively color illuminated and mounted in a lucite ring. This second meter was not read by the subject but served to provide the same level of illumination to the subject's eyes during the time the main display was concealed by the shutter. When the shutter opened for the subject to read the display, the top meter lights were automatically turned off. When the subject responded verbally, the shutter closed and the top meter lights came back on so the subject would have constant level illumination at all times.

Turbidity levels in the tank were set at two levels - - clear tap water and a very murky water. Turbidity was achieved by using Nigrosin dye to discolor the tap water. Turbidity was measured by use of the attenuation coefficient (α) as described by Duntley (1963) and Luria and Kinney (1970). The units of the attenuation coefficient (α) are natural log units per meter. The attenuation coefficient for the different levels of turbidity was converted from the percent transmission measured on a monochromatic spectraphotometer with a 10 centimeter path. Readings were taken to correspond with the spectral characteristics of the Wratten filters. The range of the attenuation coefficient for the clear and murky conditions may be seen in Table I. Since the transmittance of each of the water turbidities was very close for both the red and green spectrums, the values in Table I represent the average turbidity for the two spectrums. The spectraphotometer used was a "Spectronic 100" manufactured by Bausch and Lomb.

The illumination levels were controlled by the subjects and set at a level which the subjects felt would be a minimum acceptable level for reading the display without sacrificing speed or accuracy. (See Appendix A: Instruction)

TABLE I

RANGE OF ATTENUATION COEFFICIENT (α)

TURBIDITY LEVEL	LOW α	LOW Trans*	MEAN α	MEAN Trans*	HIGH α	HIGH Trans*
CLEAR	.16	85.1%	.35	70.8%	.50	60.5%
MURKY	5.06	.6%	5.74	.3%	6.31	.2%

* Transmittance is the average transmittance through 1 meter of water for 533.8 and 632.7 nanometers.

C. SUBJECTS

The subject field consisted of 16 males ranging in age from 22 to 36 years with a mean age of 28.7. Eleven were students at the Naval Postgraduate School, and of the remaining five, three were active military officers, one an engineer and one a graduate student in philosophy. There were no non-swimming subjects and five had extensive diving experience. None of the subjects wore glasses although two wore contact lenses for 20/20 corrected vision. No subject was color-blind. All subjects were used to reading dials in their related duty positions of aviation, navigation, etc. None had significant breathing difficulties with the face mask.

D. EXPERIMENTAL DESIGN

Twelve conditions of the display (3 illumination colors - - white, red, green - by 2 dial backgrounds - - white and black - by 2 turbidity levels - - clear and murky) were presented to each subject in two forty minute periods separated by approximately fifteen minutes (due to changing the turbidity condition). For approximately 30 minutes before testing and during the testing when displays and other variables had to be changed, all subjects wore red goggles to keep their eyes dark adapted. There were brief breaks in changing environmental conditions and no subjects complained of fatigue. The following aspects form the basis for the test design:

1. All subjects received each of the twelve conditions but in random order. Due to difficulty in changing turbidity level,

six conditions were presented in each turbidity level prior to changing that level. Data bias in turbidity was prevented by scheduling 50% of the subjects for the clear level first and conversely.

2. Each subject was tested for 20 trials at each condition. The first 10 were presented as training and learning. The last 10 composed a "data run" on a subject with a total of 1920 data points on all sixteen subjects.

3. Voltage readings to set the display numbers were selected from a table of random numbers uniformly distributed from 0.0 to 10.0.

4. Before trials began in any given condition, subjects adjusted the illumination to a level at which they felt was a minimum without sacrificing speed or accuracy of the meter readings.

5. Response times, errors, and footlamberts of illumination to obtain said illumination were the criteria on which the four variables (subjects, light illumination color, background color of display, and turbidity of water) were evaluated.

6. Environmental conditions which were held constant were: ambient illumination (total darkness), viewing distance and display size.

E. PROCEDURE

Each subject was shown the tank and the electronic apparatus and then read a set of written instructions (See Appendix A.). The experimentor was able to vary the voltmeter readings inside the tank and monitor them on a calibrated voltmeter outside the tank. On the subject's command, the tester varied the display intensity to the lowest level at which the subject could make a reading without sacrificing accuracy or speed. At least four trials were run at each condition per subject to determine stable intensity levels.

During the ten learning trials at each condition, the subject was shown errors and given an opportunity to recheck his response. In some cases subjects were given additional time to become familiar with the testing apparatus when they demonstrated minor breathing difficulties initially.

Response times (hundreths of seconds), intensity levels (volts) and errors were manually recorded by the tester. Knowing the voltage required for a given intensity level, the footlamberts of illumination at the face of the meter could be determined from previously calibrated curves. Also, knowing the transmittance of the various wavelengths in the two turbidities of water, the footlamberts, at the face mask 12 inches away, could be calculated.

III RESULTS

Response times for each subject in each condition were averaged over the correct responses to yield one data point per subject per condition. These data were then analyzed with a 2 x 2 x 3 repeated measures analysis of variance (ANOVA). See Table II. The normal standard of $p < .05$ will be used in the remainder of this paper to describe a variable as to whether or not it was significant.

The results of Table II indicate that turbidity was the only variable which had a significant effect on response times. The fact that the other variables did not influence response times is not surprising, because subjects chose the lowest level of intensity which would enable them to still make accurate and rapid responses. As such, it was expected that none of the variables would affect response times since the subjects would probably adjust the intensities to an optimal illumination level in each condition.

The mean response time for the clear turbidity condition was 1.16 seconds and 1.09 seconds for the murky condition. See Figure I. At first glance, the faster response time for the murky condition might seem unusual. However, this is not surprising to the author, because every subject seemed somewhat surprised at how dark the water appeared. Subjectively, the authors had the feeling that the subjects seemed to force themselves to try a little harder when looking through the murky turbidity condition. However, it should be pointed out that this discussion has concerned a statistical

TABLE II

ANALYSIS OF VARIANCE, RESPONSE TIMES

SOURCE	DF	MS	F	p
SUBJECTS(S)	15	0.905		
TURBIDITY(T)	1	0.257	4.59	.05
BACKGROUND(B)	1	0.0481	2.00	.25
COLOR(C)	2	0.018	1.80	.25
SxT	15	0.056		
SxB	15	0.024		
SxC	30	0.010		
TxB	1	0.005	0.238	NS
TxC	2	0.024	3.000	.10
BxC	2	0.010	1.250	NS
SxTxB	15	0.021		
SxTxC	30	0.008		
SxBxC	30	0.008		
TxBxC	2	0.00006		
SxTxBxC	30	0.006		
TOTAL	191			

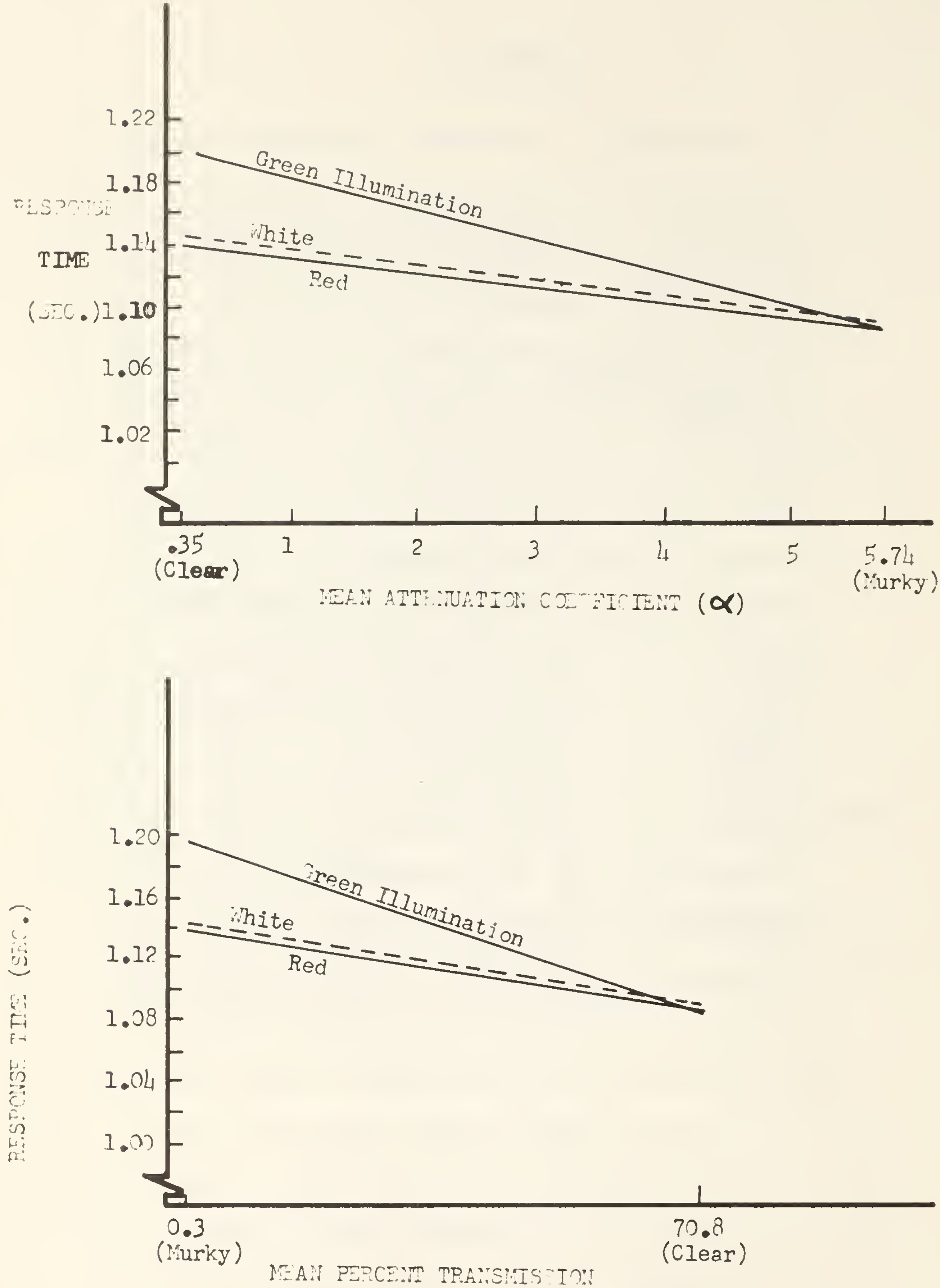

FIGURE 1. Mean Response Time Vs. Mean Attenuation Coefficient and Mean Percent Transmission

difference, and the difference of .07 seconds probably would have little significance in the real world.

The response times in this investigation averaged 1.13 seconds which agrees closely with the results of Miller and Kirtz (1972). The reason for this is probably due to the coordination between the investigators in trying to standarize experimental conditions. Both experiments maintained a constant illumination into the subjects eyes at all times, whereas Poock and Ruckner (1972) did not illuminate the subjects eyes with the same intensity of illumination between trials as during trials. Between trial illumination was approximately one quarter that during trials. In that experiment, their average response time was 1.85 seconds and could have been such due to an adaptation required of the eye each time the display was presented. It should also be kept in mind that in the present experiment, subjects adjusted their illumination levels to what they believed minimum for maintaining speed and accuracy. Table III shows the results of an analysis on the light levels which were available at the face mask 12 inches from the display. (At the sponsor's request, the original light levels were measured directly next to the display meter so that power needed to run the display could be analyzed. However, knowing the distance the light travelled and the transmittance of the water for the red and green colors, one can easily convert to the light levels 12 inches away at the face mask.) For white transmittance, the authors were told by physicists

TABLE III

ANALYSIS OF VARIANCE, INTENSITY (FOOTLAMBERTS) AT FACE MASK

SOURCE	DF	MS	F	p
SUBJECTS(S)	15	.00992		
TURBIDITY(T)	1	.00604	2.11	NS
BACKGROUND(B)	1	.21127	54.7	.001
COLOR(C)	2	.06314	19.1	.001
SxT	15	.00286		
SxB	15	.00386		
SxC	30	.00331		
TxB	1	.01619	10.6	.01
TxC	2	.03908	22.6	.001
BxC	2	.03354	16.9	.001
SxTxB	15	.00153		
SxTxC	30	.00173		
SxBxC	30	.00198		
TxBxC	2	.02910		
SxTxBxC	30	.00149		
TOTAL	191			

and chemists to average the transmittance for 400,533.8, and 700 nonometers since these three combined in equal portions would approximately simulate white light.

Table III indicates no significant difference between the footlamberts of light to which subjects adjusted the intensity in the clear and murky water turbidities. Thus, the difference in response times for the clear and murky turbidities appears to have not been influenced by light intensity used in those two conditions.

The response times for the color of illumination and background color of the meter display did not, as previously mentioned, influence response times in a significant manner. These results are depicted in Figure 2. In summary, the results indicate that for all practical purposes, the subjects adjusted the light levels under each experimental condition to such a degree that response times were very similar under all conditions. The implication is that subjects were quite good at adjusting the light intensity to a level under all conditions which would not degradate response times.

The analysis of the intensity levels set by the subjects shows a difference in both display background and color of illumination. These results are shown in Figure 3. A closer look at the data reveals the white background illumination settings averaged .09, the red .03 and the green .06 footlamberts respectfully. A Duncan Multiple Range test showed all three footlambert levels at each of the colors to be significantly different from each other at the .05 level.

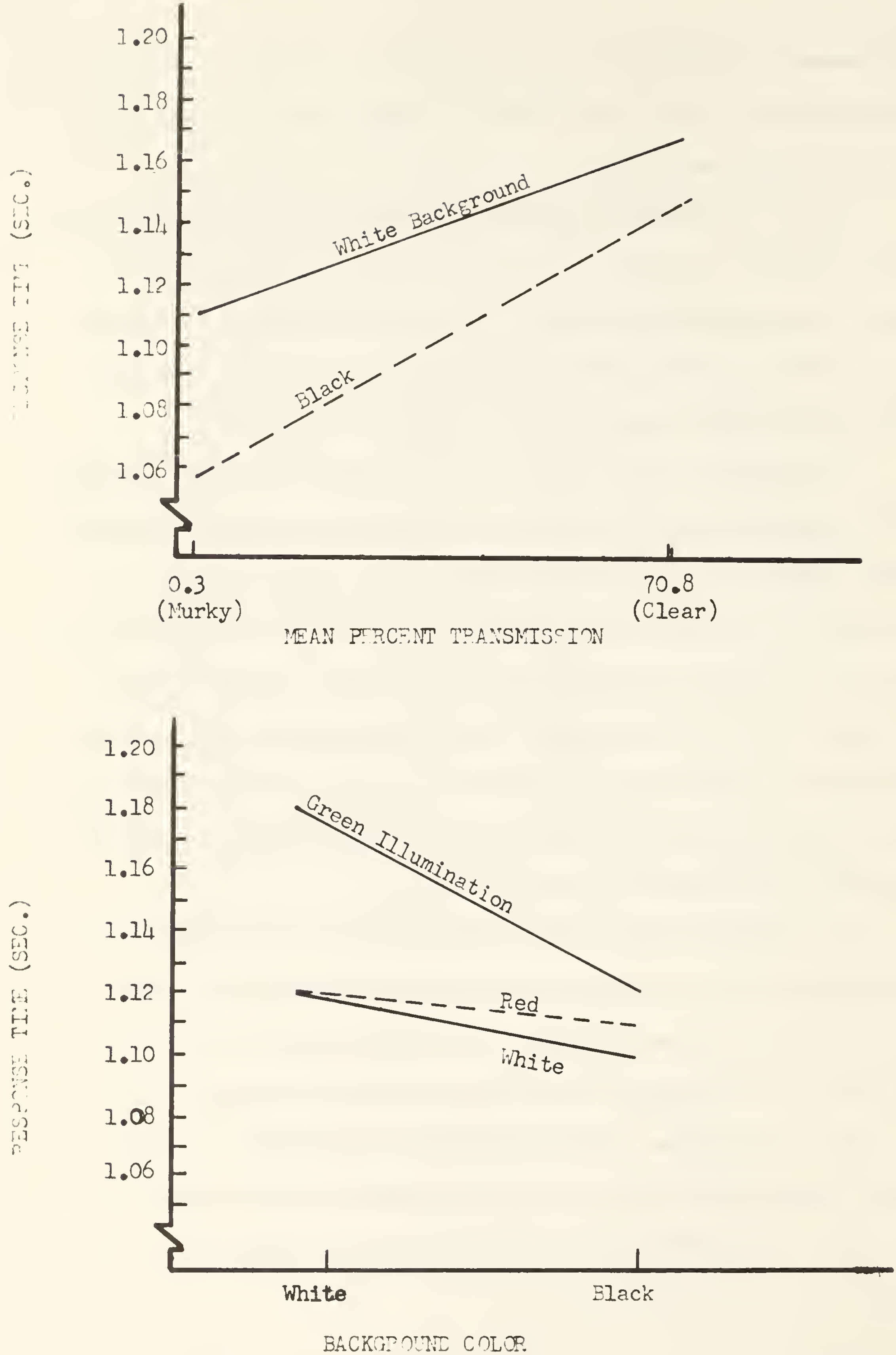

FIGURE 2. Mean Response Time Vs. Mean Percent Transmission And Background Color

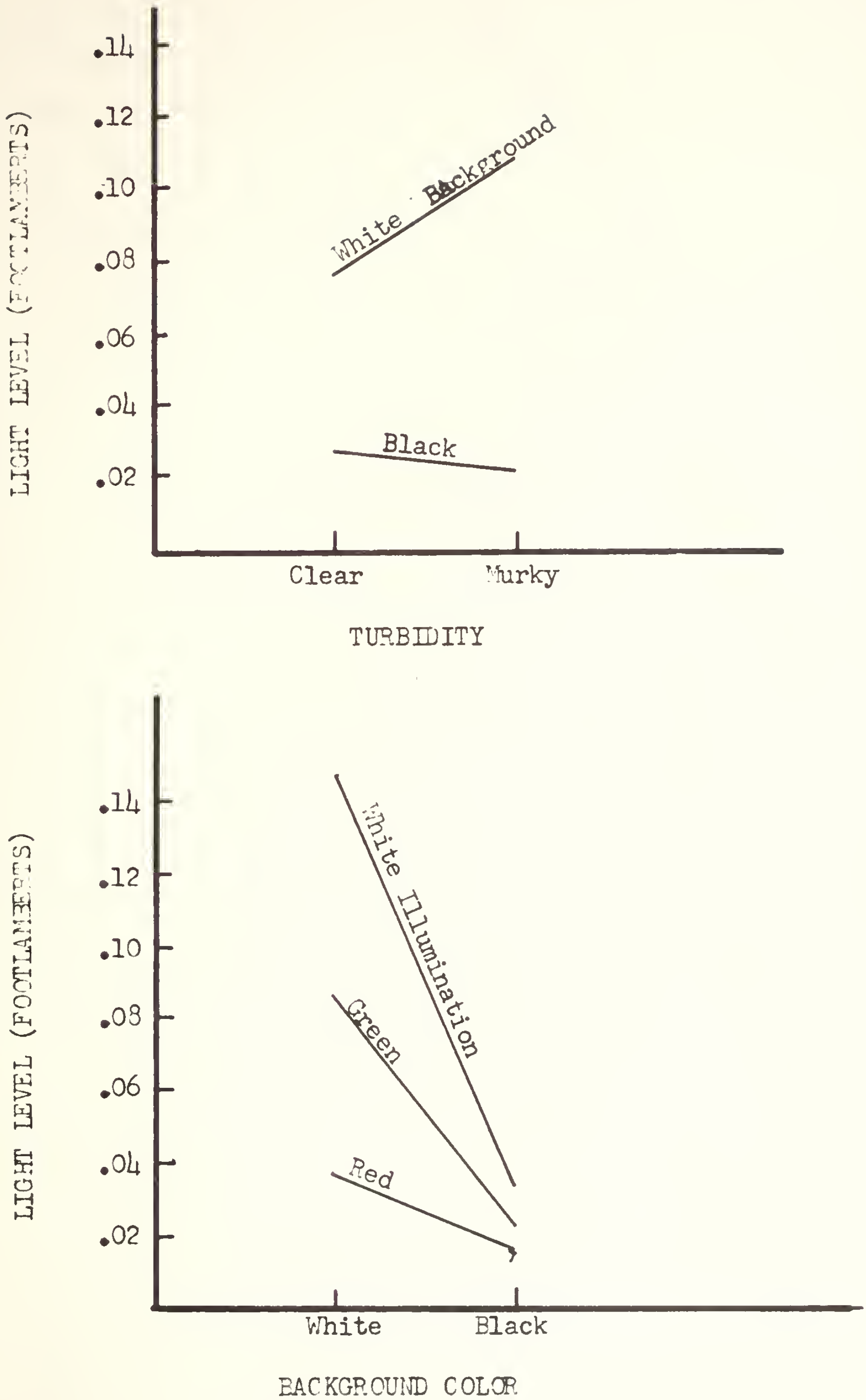

FIGURE 3. Background Intensity Vs. Turbidity And Background Color

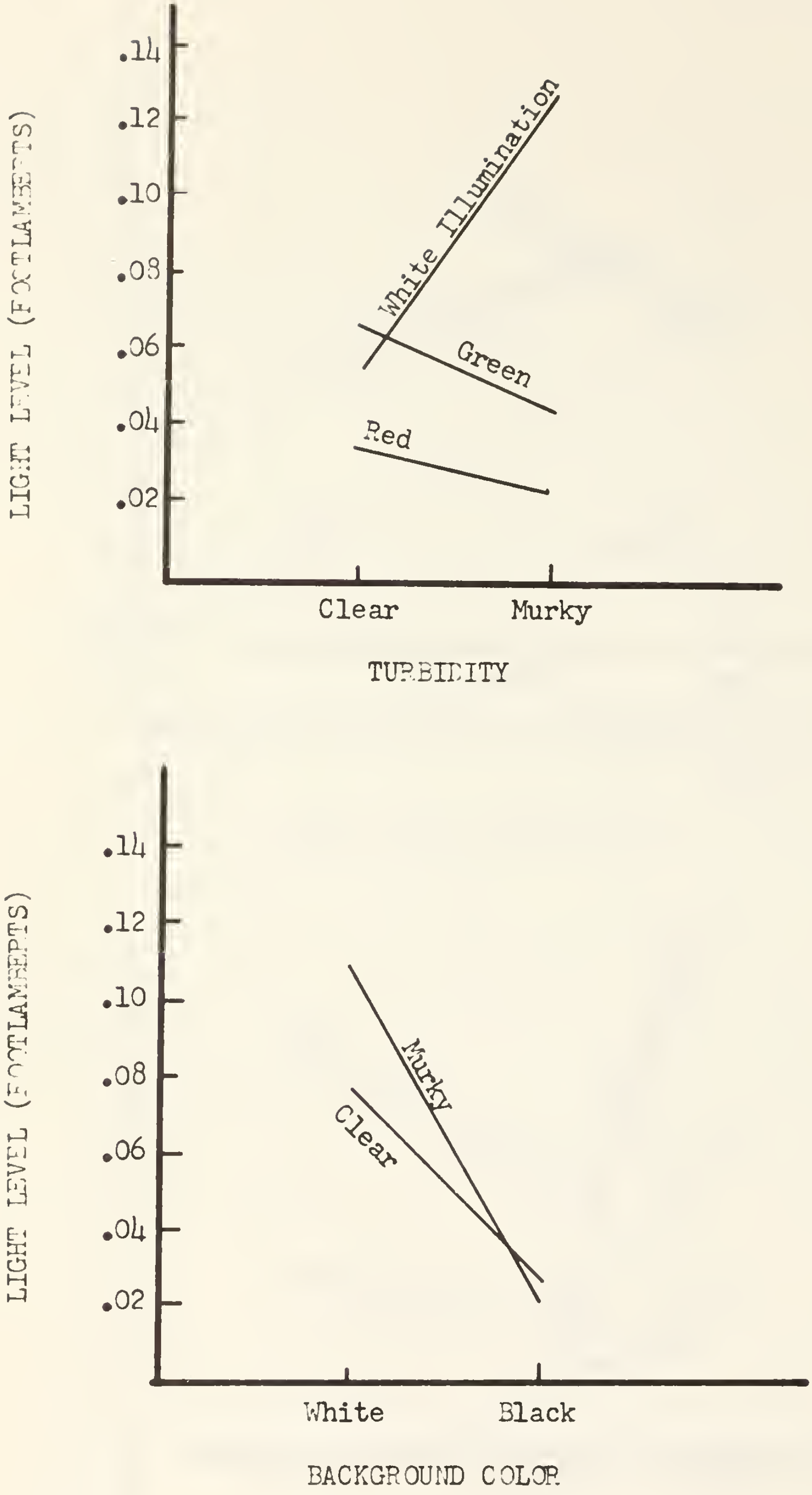

FIGURE 4. Background Intensity Vs. Turbidity And Background Color

The white background display was set at an average of .09 footlamberts which was significantly higher than that of the black background which averaged a setting of .02 footlemberts. In other words, even though response times were similar, subjects needed the white background brighter to obtain equivalent response times.

Table III also indicates that three of the two way interactions were significant. These interactions are depicted in Figures 3 and 4. However, these appear to be statistical interactions and do not really represent strong interactions in the real world within the limits of the variables studies. For example, the top graph of Figure 4 shows that under clear turbidity conditions, white illumination is less than green illumination but the difference is only .01 footlamberts while the situation is much greater and reversed under the marky turbidity condition. Likewise, the bottom graph of Figure 4 shows an interaction with subjects setting less footlamberts under the black background with murky water than for clear water but the difference was only .007 footlamberts as compared to the reversed difference under the white background condition.

The power required to generate the above intensity levels appears to be comparable between this experiment and that of Miller and Kirtz (1972). Using parallel wiring of the G.E. No. 44 bulbs used in this experiment, the bulbs draw approximately .25 amps when fully warmed up at 6.3 volts as per advice given by electronic technicians. The average voltage level in this experiment was 2.94 volts to run the color illumination. Therefore, the average power required was .345 watts ($P = I^2R$) since the resistance of the bulbs is 25.2 ohms. The G.E. No. 387 bulb of Miller and Kirtz draws .04 amps when fully warmed up at 28 volts. Their average voltage needed was 15.8 volts with a resulting power requirement of .364 watts since the G.E. No. 387 has a resistance of 700 ohms.

Thus, a generalization of the mean power requirements would suggest that, for at least the two types of displays and bulbs discussed above, the average power requirements are very close and other factors will probably be of more importance. However, this would depend on the particular power requirements for a given vehicle design and the particular colors of illumination to be used.

An analysis of the errors indicated no significant differences in the error rate between any levels of the experimental variables. An observation was counted as an error anytime the reading deviated over .2 volts from the reading set on the display meter. Any deviations of .2 volts or less could have been caused by subject head movement or differences in the display meter and the monitor meter which the experimenter viewed outside the tank.

Most subjects made very few if any errors and as such the individual distribution of errors in Table IV cannot be considered normally distributed. As a result, the error data in Table IV was analyzed by a chi-square test and none of the experimental parameters exhibited an influence on the error rate. Thus, as in Poock and Ruckner (1972), no variables had a greater or lesser effect on the error rate which was .092 errors per trial. This rate was approx-

TABLE IV

TOTAL ERRORS OVER .2 VOLTS

TURBIDITY		COLOR: WHITE	RED	GREEN
	CLEAR	23	25	37
	TURBID	32	26	34

DIAL BACKGROUND		COLOR: WHITE	RED	GREEN
	WHITE	22	25	36
	BLACK	33	26	35

DIAL BACKGROUND		TURBIDITY: CLEAR	TURBID
	WHITE	40	43
	BLACK	45	49

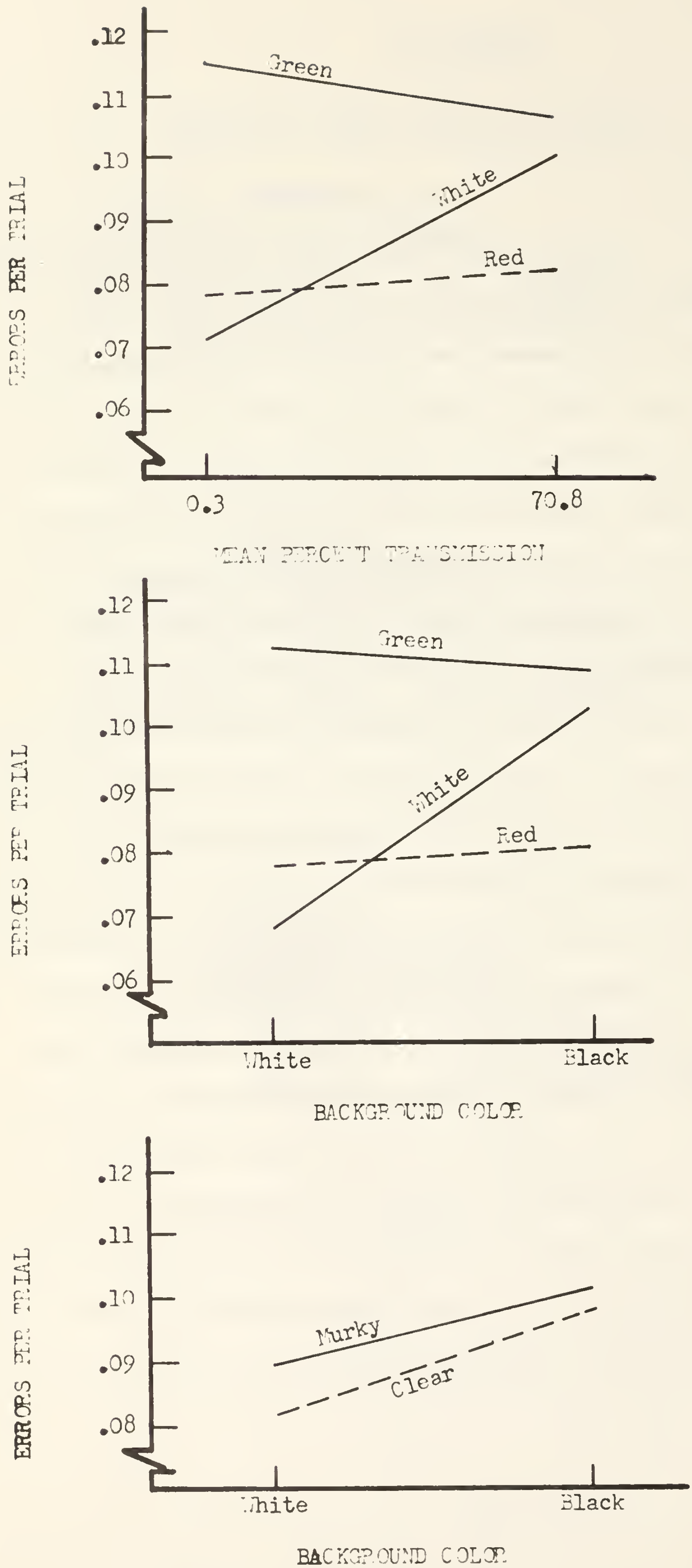

FIGURE 5. Error Rate Graphs

imately 2.5 times larger than Poock and Ruckner's earlier results but there are probably many factors which could have caused this difference. These rates can be compared subjectively with those of Miller and Kirtz (1972) in which their average error rate was .12 errors per trial. These are all in the same general realm and can begin to give the designer an idea that one might expect error rates somewhere from three to twelve percent under similar conditions. Figure 5 graphically represents the error rates of this experiment.

Observation of the data also indicated no learning taking place throughout the twenty trials. To provide an analytical indication of the learning, if any, eight of the runs which appeared to maybe contain some learning were analyzed. A "t" test between the first ten trials and the second ten trials of each of these "extreme" cases, indicated no difference in the means of the first and second set of ten trials for any of the runs. This confirmed the subjective observations of the data and implied no learning effects. Researchers in the future should be able to discount any learning effects and use, for example, twelve trials with the last ten being used as good data.

IV. SUMMARY

This investigation in underwater visibility is different from other studies because subjects were allowed to choose their own level of illumination once the other experimental parameters had been set. As such, it is difficult to compare these results with those of other investigators because a variable that would cause differences in other experiments could easily have been normalized in this experiment by the subject setting an intensity level which equalized a given parameter's effects.

In summary, response times were constant under all conditions except for turbidity levels which had .07 seconds difference and the practical effect of this difference in the real world is probably negligible.

Since the response times are very similar for all colors of illumination, the next question would be to see which of the illumination colors required the least power. White Illumination required the least power, .238 watts, followed by red at .363 watts and green at .445 watts. Thus, from a power point of view, one should use white lighting and combine this with a black background on the instrumentation to maintain a covert atmosphere, since there was no difference in the white versus black background. This design should be practical also since none of the variables contributed a significant amount of errors in comparison to the other variables.

APPENDIX A

INSTRUCTIONS TO SUBJECTS

You are a subject in an experiment to test your responses to a visual underwater stimulus. There will be differing environmental conditions of the murkiness of the water, background of the instrument face and the light color illuminating the dial.

Assume a comfortable sitting position with your eyes and nose in the face mask. No light should leak around your face and you will have to breathe through your mouth. Should you have difficulty doing this, a nose clip is available. If the face mask becomes fogged at any time, notify the tester immediately.

In front of you, notice the grey plastic shutter directly in the center of the mask at eye level and an illuminated non-functioning dial face to the upperleft corner of the face mask. When the shutter is released, you will observe a functioning circular voltmeter at the same illumination intensity as the non-functioning meter which can no longer be seen.

The first task is to adjust the illumination of the voltmeter. As the source which supplies voltage to light the meter also supports other important components in the system, it is imperative to limit the illuminating voltage as much as possible without sacrificing your speed or accuracy in reading the meter. The tester will adjust the illumination at your command. Initially, the light will be extremely bright and then be lowered until you command "stop" at the lowest level you can read accurately. Several adjustments will be made from bright to dim and conversely until a stable illumination level is obtained. For fine adjustments, you should instruct the tester to go "up" or "down" until you are satisfied. This procedure will be repeated when any of the environmental conditions are changed and it is extremely important to correctly adjust the illumination so as not to impair your performance.

Your primary task is to correctly read the meter and give a verbal response of what you saw. Your response will trigger the shutter via the microphone and electrical circuit. The word "top" has been found to be especially suitable as an initial triggering command. A typical response might be: "Top!, 5.4".

Avoid coughing, thinking out loud, or making any other noise which will cause the shutter to close before you are ready. Do not remove your face from the mask until told to do so. Work as quickly as possible but try to make your response accurate. Notify the tester immediately of any difficulties you encounter, or if any of the testing procedures are confusing to you.

APPENDIX B

MEAN DATA FOR RESPONSE TIMES (SEC)

TURBIDITY

DIAL BACKGROUND →

COLOR OF ILLUMINATION	CLEAR		MURKY	
	WHITE	BLACK	WHITE	BLACK
WHITE	1.15	1.14	1.10	1.08
RED	1.15	1.13	1.10	1.07
GREEN	1.23	1.18	1.12	1.05

MEAN DATA FOR ILLUMINATION AT THE FACE MASK

(FOOTLAMBERTS)

TURBIDITY

DIAL BACKGROUND →

COLOR OF ILLUMINATION	CLEAR		MURKY	
	WHITE	BLACK	WHITE	BLACK
WHITE	.080	.038	.215	.034
RED	.045	.022	.033	.012
GREEN	.104	.030	.070	.017

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DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Naval Postgraduate School Monterey, California 93940	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

Underwater Display Visibility as Influenced by Turbidity, Display Background Color, and the Color and Intensity of Illumination.

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Technical Report

5. AUTHOR(S) (First name, middle initial, last name)

Gary K. Poock

6. REPORT DATE July 1972	7a. TOTAL NO. OF PAGES 37	7b. NO. OF REFS 5
8a. CONTRACT OR GRANT NO. b. PROJECT NO. WR-2-9081 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Naval Electronics Laboratory Center San Diego, California

13. ABSTRACT

The purpose of this study was to determine the effects of water turbidity, display background color, and the color and intensity of illumination on a visual reading task in a dark, flooded environment. The reading task was to read a voltmeter and make a correct oral report of the reading.

The sixteen subjects used in this study were allowed to set the intensity at a level which they felt was the minimal needed without sacrificing accuracy or speed in the reading task. As was expected, the results show no difference in the effects of the other variables since subjects apparently adjusted the intensity to a level which equalized the effects of the other variables in any given condition. There was a significant statistical difference in the response times under the two water turbidities used but this difference was only .07 seconds.

The error rate was constant, with no variable having a greater effect on the error rate than did other variables. The expected error rate over all variables was .092 errors per each trial taken.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Underwater Vision Turbidity Underwater Illumination Underwater Intensity						

DD FORM 1 NOV 65 1473 (BACK)
S/N 0101-807-6821

A-31409